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Performance Evaluation of Voltage Stability Indices for Dynamic Voltage Collapse Prediction

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Abstract: The research presents a study in evaluating the performance of several voltage stability indices used for dynamic voltage collapse prediction in power systems. A new voltage stability index has been proposed and it is named as the power transfer stability index. The proposed index is then compared with other known voltage stability indices such as the voltage collapse prediction index, the line index and the power margin. To evaluate and compare the effectiveness of these indices in predicting proximity to voltage collapse, simulations are carried out using the WSCC 9 bus test system. Simulation test results show that the proposed power transfer stability index and the voltage collapse prediction index give a better prediction of dynamic voltage collapse compared to the power margin and the line index.

Key words: Dynamic voltage collapse, voltage stability index, power system dynamics

INTRODUCTION

During the last few years, the restricted growth of electric transmission system and increasingly higher power demands have forced utilities to operate power networks relatively close to their transmission limits. As system load increases, voltage magnitudes throughout a power network will slowly decline and continuing increase in loads may eventually drive a power system to a state of voltage instability and may cause a voltage collapse. Recent blackouts around the world are mainly due to voltage collapse occurring in stressed power systems which are associated with low voltage profiles, heavy reactive power flows, inadequate reactive support and heavily loaded systems. The consequences of voltage collapse often require long system restoration while large groups of customers are left without supply for extended periods of time. Therefore, the study of voltage instability and voltage collapse is still a major concern in power system operation and planning.

Several different approaches have been proposed for predicting the occurrence of voltage collapse in which majority of the works addressed in the literature treat the voltage instability problem using static analysis methods based on the conventional power flow model. The static analysis of the voltage instability problem produces useful results but it does not take into account dynamic aspects of the problem. Power system is a typical large dynamic system in which the dynamic behavior of its power components has a significant influence on voltage collapse. Currently, voltage stability is widely accepted as being a dynamic phenomena and therefore it is necessary to consider dynamic system model including generator, governors, exciters and induction motor loads. To incorporate the dynamic aspects of a power system into voltage stability analysis, the time domain simulation technique is normally used. The technique requires appropriate modeling so as to provide an accurate replication of actual dynamics of voltage instability.

Some research is currently in progress world-wide to focus on how to estimate dynamic voltage stability margin accurately and efficiently for predicting the occurrence of dynamic voltage collapse. Some of the known methods for predicting proximity to voltage collapse are by using eigenvalue analysis (Heideman *et al*., 2000; Cai and Elrich 2004; Teeuwsen *et al*., 2005) and the use of voltage stability indices such as power margin (Julian *et al*., 2000; Bergovic *et al*., 2002), line (L) index (Huang and Nair, 2001) and voltage collapse prediction index (VCPI) (Balamourougan *et al*., 2002). In this study, a new index for dynamic voltage collapse prediction named as the Power Transfer Stability Index (PTSI) is proposed and presented. To investigate the effectiveness of the proposed voltage collapse indicator, a comparison is made with the known three dynamic voltage stability indices that have been proposed in the literature, namely, the power margin, L index and VCPI. The objective of the study is to evaluate the performance these voltage stability indices in predicting proximity to dynamic voltage collapse.

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INDICES FOR DYNAMICS VOLTAGE COLLAPSE PREDICTION

The derivation of the proposed voltage stability index named as PTSI is given. The other indices that have been proposed by other researchers namely the power margin (Julian*et al*., 2000), L index (Huang and Nair, 2001) and VCPI (Balamourougan *et al*., 2004) are also described because these indices are used for the purpose of comparison.

Power transfer stability index: The proposed Power Transfer Stability Index (PTSI) is derived by first considering a simple two-bus Thevenin equivalent system, where one of the buses is a slack bus connected to a load bus by a single branch as shown in Fig. 1.

From Fig. 1, the current drawn by the load is given by,

$$\bar{I} = \frac{\bar{E}_{Thev}}{\bar{Z}_{Thev} + \bar{Z}_L} \tag{1}$$

The load power can be written as,

$$\bar{S}_L = \bar{Z}_L \bar{I}\,\bar{I}^* = \bar{Z}_L \left|\bar{I}\right|^2 \tag{2}$$

Substituting Eq. 1 into 2 we get,

$$\bar{S}_L = \bar{Z}_L \left|\frac{\bar{E}_{Thev}}{\bar{Z}_{Thev} + \bar{Z}_L}\right|^2 \tag{3}$$

Considering that $\bar{Z}_L = Z_L \angle\alpha$ and $\bar{Z}_{Thev} = Z_{Thev}\angle\beta$ and substituting them into Eq. 3, we get,

$$\bar{S}_L = Z_L\angle\alpha \left|\frac{E_{Thev}}{Z_{Thev}\angle\beta + Z_L\angle\alpha}\right|^2 \tag{4}$$

where, α is phase angle of the load impedance and ß is phase angle of the Thevenin impedance.

The magnitude of load apparent power S_L from Eq. 4 can be expressed as,

$$S_L = \frac{E^2_{Thev} Z_L}{\left|Z_{Thev}\angle\beta + Z_L\angle\alpha\right|^2} \tag{5}$$

Simplifying Eq. 5 we get,

$$S_L = \frac{E^2_{Thev} Z_L}{Z^2_{Thev} + Z_L{}^2 + 2Z_{Thev}Z_L\cos(\beta-\alpha)} \tag{6}$$

Determine the maximum load apparent power S_L by differentiating Eq. 6 with respect to the load impedance Z_L,

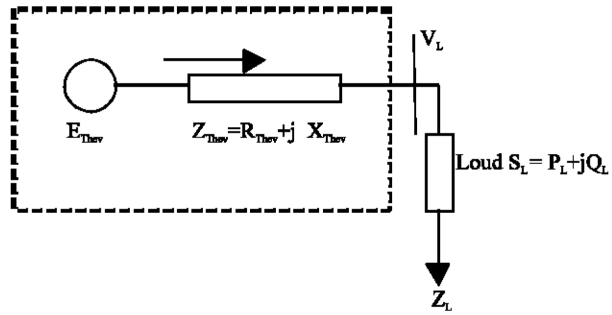


Fig. 1: Simple two-bus Thevenin equivalent system

$$\frac{\partial S_L}{\partial Z_L} = \frac{E^2_{Thev}\left(Z^2_{Thev} - Z^2_L\right)}{\left[Z^2_{Thev} + Z^2_L + 2Z_{Thev}Z_L\cos(\beta-\alpha)\right]^2} \tag{7}$$

S_L has maximum value when $\partial S_L/\partial Z_L = 0$, hence,

$$\frac{\partial S_L}{\partial Z_L} = \frac{E^2_{Thev}\left(Z^2_{Thev} - Z^2_L\right)}{\left[Z^2_{Thev} + Z^2_L + 2Z_{Thev}Z_{L0}\cos(\beta-\alpha)\right]^2} = 0 \tag{8}$$

From Eq. 8, the point of maximum loadability can be determined when

$$Z^2_{Thev} - Z^2_L = 0 \text{ or } Z_L = Z_{Thev}$$

The maximum load apparent power S_{Lmax} is then determined by substituting $Z_L = Z_{thev}$ into Eq. 6 and simplifying it further, we get,

$$S_{Lmax} = \frac{E^2_{Thev}}{2Z_{Thev}(1+2\cos(\beta-\alpha))} \tag{9}$$

The maximum load apparent power given by Eq. 9 is also considered as the maximum loadability limit which depends on the Thevenin parameters that vary with system operating conditions.

To assess the load bus distance to voltage collapse, a power margin is defined as $S_{Lmax} - S_L$ in which the margin is equal to 0 if $Z_L = Z_{Thev}$. For power margin values equal to 0, it indicates that no more power can be transferred at this point and a proximity to voltage collapse is said to occur. Thus, to prevent a power system from voltage collapse, the power margin has to be greater than zero. In other words, the ratio of S_L to S_{Lmax} has to be less than 1.0. However, a voltage collapse will occur if the ratio of S_L to S_{Lmax} is equal to 1, that is,

$$\frac{S_L}{S_{Lmax}} = 1 \tag{10}$$

Substituting Eq. 6 and 9 into 10 we get,

$$\left[\frac{E_{Thev}^2 Z_L}{Z_{Thev}^2 + Z_L^{\ 2} + 2Z_{Thev}Z_L\cos(\beta-\alpha)}\right]\left[\frac{2Z_{Thev}\left(1+\cos(\beta-\alpha)\right)}{E_{Thev}^2}\right] = 1 \quad (11)$$

Simplifying Eq. 11, we get

$$\frac{2S_L Z_{Thev}\left(1+\cos(\beta-\alpha)\right)}{E_{Thev}^2} = 1 \quad (12)$$

Using Eq. 12, the proposed voltage collapse index named as the Power Transfer Stability Index (PTSI) is defined as,

$$PTSI = \frac{2S_L Z_{Thev}\left(1+\cos(\beta-\alpha)\right)}{E_{Thev}^2} \quad (13)$$

The value of PTSI will fall between 0 and 1. When PTSI value reaches 1, it indicates that a voltage collapse has occurred.

Power margin: The power margin index is used to track the closeness to voltage collapse and is based on the distance of apparent power (Julian *et al.*, 2000). It is derived from the concept of voltage instability predictor, in which, the proximity to voltage collapse is expressed in terms of distance between two voltage curves or between two impedance curves (Bergovic *et al*., 2002). The power margin describes the proximity to voltage collapse in terms of power and can be looked upon as the power available before a power system collapses. It is defined as the power difference between the maximum apparent power and the actual power. Power margin can also be defined as the extra MVA that can be delivered to the load before voltage collapse occurs (Bergovic *et al.*, 2002). Mathematically, the power margin is given by,

$$\Delta S_L = Z_L I^2 - Z_{Thev} I^2 \quad (14)$$

where,
ΔS_L is the power margin at bus L
Z_L is the load impedance at bus L
Z_{Thev} is the equivalent network impedance
I is the current measured at bus L

From Eq. 14, it can be noted that when the power margin approaches zero, it means that no more power can be increased and system collapse will occur if additional power is increased.

Line index: The line (L) index (Huang and Nair, 2001) can be derived from a two bus system model and generalized for a multi-node power system. The index is simple to calculate because it utilizes information obtained from a normal load flow solution. The L index calculated for each bus j is given by,

$$L_j = \left|\frac{S_j^+}{\left(Y_{jj}^{+} * .V_j^2\right)}\right| \quad (15)$$

where,
S^+_j the transformed injected complex power
Y^+_{jj} the transformed admittance given by the equation $Y^+_{jj} = 1/Z_{jj}$
V_j is the complex voltage at bus j
The transformed power S^+_j consist of two parts,

$$S_j^+ = S_j + S_j^{cor} \quad (16)$$

for which S_j^{cor} is given by,

$$S_j^{cor} = \left[\sum_{i\in\alpha L}\frac{Z_{ji}^*}{Z_{jj}^*}.\frac{S_i}{V_i}\right]V_j \quad (17)$$

where, Z_{ji}, Z_{jj} are the off diagonal and diagonal elements of the impedance matrix, respectively. α_L is a set of load buses and V is a complex voltage. V_j is affected by bus power S_j and S_j^{cor} equivalent power , which stems from the other loads in a system.

The values of L index vary in the range between 0 (no load condition) and 1 (voltage collapse condition). For a stable situation, the condition $L_j \le 1$ must not be violated at any of the node j.

Voltage collapse prediction index: The calculation of Voltage Collapse Prediction Index (VCPI) requires the voltage phasor information of the participating buses in a system and network admittance matrix. The VCPI index for bus k is given by Balamourougan *et al.* (2004),

$$VCPI_k = \left|1 - \frac{\sum_{\substack{m=1\\m\neq k}}^{N} V'_m}{V_k}\right| \quad (18)$$

V'_m in Eq. 18 is given by

$$V'_m = \frac{Y_{km}}{\sum_{\substack{j=1\\j\neq k}}^{N} Y_{kj}} V_m \quad (19)$$

where,
V_k is the voltage phasor at bus k
V_m is the voltage phasor at bus m
Y_{km} is the admittance between bus k and bus m
Y_{kj} is the admittance between bus k and bus j
k is the monitoring bus
m is the other bus connected to bus k

The value of VCPI varies between 0 and 1. If the index is zero, the voltage at bus k is considered stable and if the index is unity, a voltage collapse is said to occur.

DYNAMIC VOLTAGE STABILITY ANALYSIS

In the dynamic voltage stability analysis, dynamic power system model including generator, exciter, governor and dynamic loads have been considered. The dynamic power system models, test system considered in the study and the procedures for the dynamic simulation of voltage collapse are described accordingly.

Dynamic models for generator and load: The generator governor model using the mechanical-hydraulic governor for hydraulic turbine (Kundur, 1994) as shown in Fig. 2a and the excitation system model using IEEE type AC1A as shown in Fig. 2b are considered in the simulation.

The governor and excitation system parameters used in the simulations are given as shown in Table 1 and 2, respectively (Kundur, 1994).

The load model considered is the composite load which is given by,

$$P = P_o\left(\frac{V}{Vo}\right)^{np} \tag{20}$$

$$Q = Q_o\left(\frac{V}{Vo}\right)^{nq} \tag{21}$$

P_o and Q_o are the active and reactive load powers at initial condition, np and nq are the load parameters obtained from the slopes dP/dV and dQ/dV, respectively. For the case where np and nq are equal to 0, 1, 2, the load model will represent constant power, constant current and constant impedance loads, respectively. For the

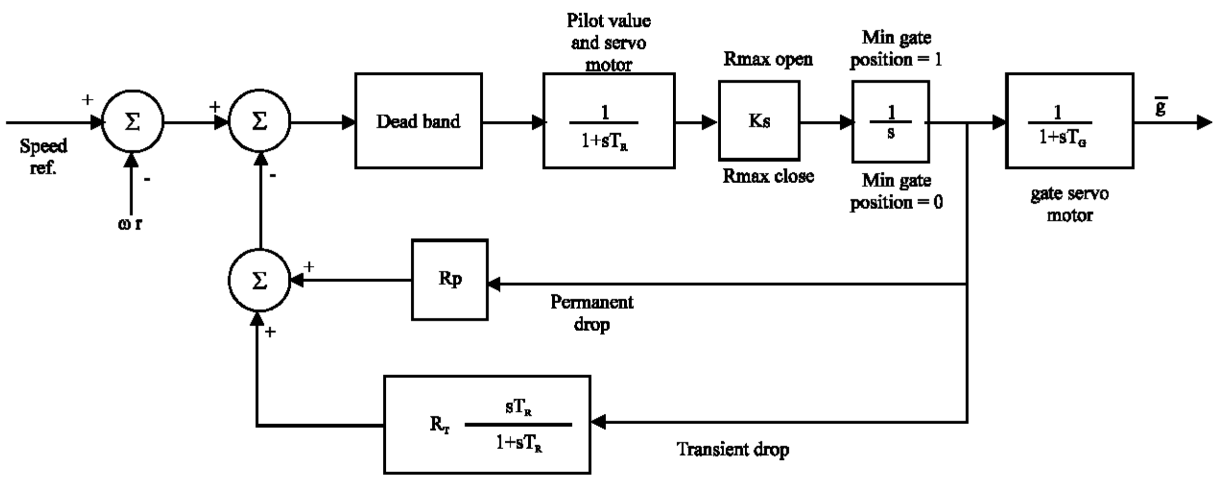


Fig. 2a: Governor model for hydraulic turbine

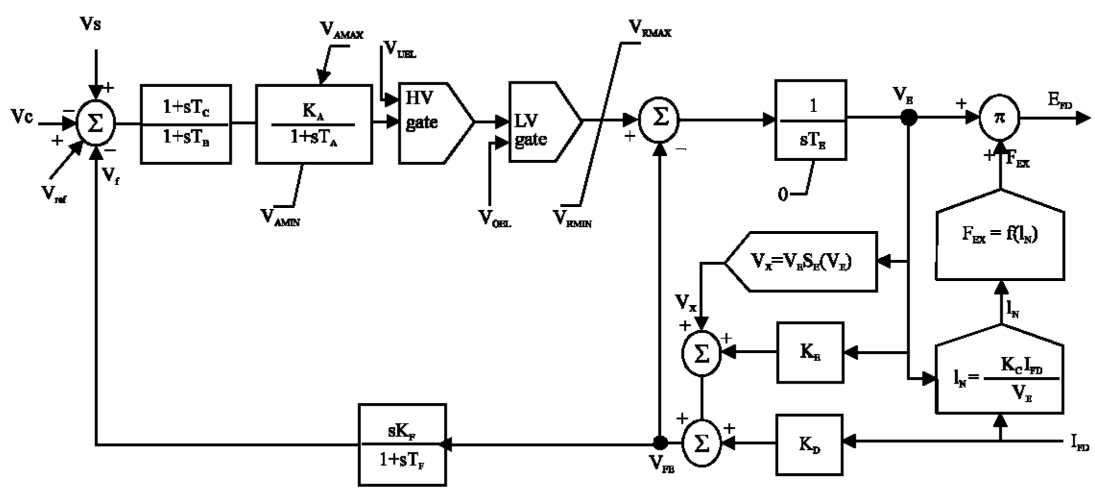


Fig. 2b: Excitation system model IEEE ACIA

Table 1: Governor parameters

Servo gain Q	Dashpot reset time T_R	Temporary drop R_T	Main servo time constant T_G	Pilot valve and servo time constant T_P	Permanent drop R_P
5	5 sec	0.4 pu	0.2 sec	0.05 sec	0.04 pu

Table 2: Excitation system parameter

Rate feedback gain K_F	Rate feedback constant T_F	Regulator gain K_A	Regulator time constant T_A	Lag time constant T_B	lead time constant T_C	Max regulator output VR_{MAX}	Min regulator output VR_{MIN}
0.03 pu	1.0 sec	400 pu	0.02 sec	0 sec	0 sec	7.3 pu	-6.6 pu

Table 3: Load parameters

Load Component	Load Type	np	Nq
Air Conditioner	Composite	0.5	2.5
Fluorescent Lighting	Composite	1.00	3.00
Pumps, fan	Composite	0.08	1.6
Large Industrial Motor	Composite	0.05	0.5
Small Industrial Motor	Composite	0.1	0.6
Resistance Space heater	Constant impedance	2.0	0.0

Table 4: Line parameters

Line	Resistance (pu)	Reactance (pu)	Susceptance (pu)	MVA rating
1-4	0.0000	0.0576	0.0000	250
4-5	0.0170	0.0920	0.1580	250
5-6	0.0390	0.1700	0.3580	150
3-6	0.0000	0.0586	0.0000	300
6-7	0.0119	0.1008	0.2090	150
7-8	0.0085	0.0720	0.1490	250
8-2	0.0000	0.0625	0.0000	250
8-9	0.0320	0.1610	0.3060	250
9-4	0.0100	0.0850	0.1760	250

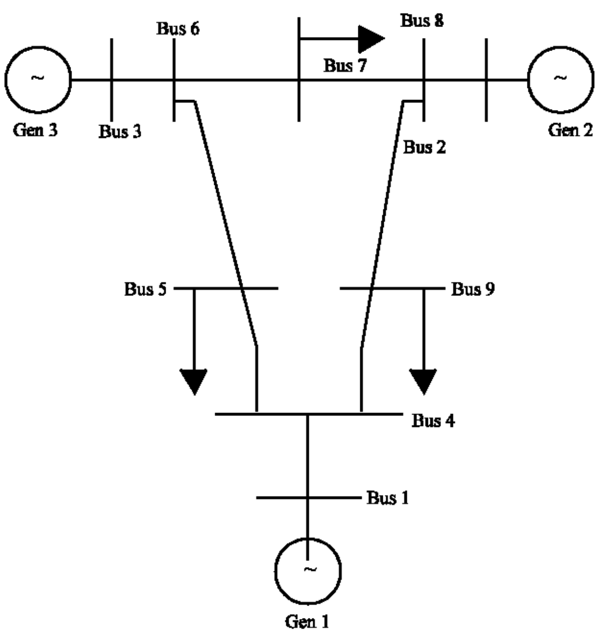


Fig. 3: The 9 bus test system

composite load, the exponent np is usually in the range of 0.5 to 1.8 and the exponent nq is typically between 1.5 and 6 (Kundur, 1994). The load model parameters considered in the simulation study are given as in Table 3.

Test system: The 9 bus test system used in the dynamic simulation of voltage collapse is shown in Fig. 3. The line parameters for the system are shown as in Table 4. The system consists of three generators connected at buses 1, 2 and 3.

Generator 1, generator 2 and generator 3 are of ratings 250 MVA, 300 MVA and 150 MVA, respectively with their inertia constants (H) of 23.64 MW-s/MVA, 6.4 MW-s/MVA and 3.01 MW-s/MVA, respectively.

The load types considered at bus 5 is a composite load and at bus 7 and 9 are static loads with values of 1+j 0.35 per unit and 1.25+j 0.50 per unit MVA, respectively at a base of 100 MVA.

Procedure for dynamic simulation of voltage collapse: The dynamic simulation of voltage collapse has been carried out using the electromagnetic transient program EMTDC/PSCAD. The procedures involved in the dynamic simulation of voltage collapse are described as follows:

- Input load, generator and line data of the test system.
- Create a contingency such as step increase in load, line outage or generator outage.
- Run the simulation for time duration from t = 5 to 80 sec.
- At every time step of 1 sec, measure the voltage, current, real power and reactive power at the monitoring bus. In this case, for the 9 bus test system, bus 5, 7 and 9 have been considered as the monitoring buses.
- Using the data obtained from step (iv), calculate the Thevenin voltage, E_{Thev}. and Thevenin impedance, Z_{Thev} at every bus measured in every second. The Thevenin voltage and Thevenin impedance are required for the calculation of the indices PTSI, VCPI and power margin.
- Calculate the indices PTSI, VCPI, L index and power margin for every time step of 1 sec.
- Plot the indices against time.
- Repeat steps (ii) to (vii) by considering another contingency.

TEST RESULTS

The performance and effectiveness of the proposed voltage stability index for predicting the proximity to dynamic voltage collapse has been evaluated by simulating the 9 bus test system. The proposed index known as PTSI is then compared with other known indices such as the power margin, L index and VCPI and the results are presented accordingly. In the dynamic simulation of voltage collapse, three contingency cases have been considered in which the first, second and third contingency cases consider load increase at bus 5, line outage at line connecting bus 4 to bus 5 and generator outage at bus 3, respectively.

Results due to load increase at bus 5: In the simulation considering the first contingency, the composite load at bus 5 is increased at a rate of 0.011 + j0.011 per unit MVA/sec from an initial load of 0.558 + j0.441 per unit MVA for a duration of time t = 10 to 80 secs. The voltage stability indices PTSI, VCPI, L index and power margin are plotted against time for indices at the load buses 5, 7 and 9 as shown in Fig. 4a-d, respectively. From the figure, it can be seen that the PTSI, VCPI and L indices increase with time as loads are increased whereas the power margin decreases with time. Comparing the indices at bus 5, 7 and 9, it can be seen that the PTSI, VCPI and L indices at bus 5 give the highest values and the power margin at bus 5 gives the lowest value compared to the indices at bus 7 and 9 due to the fact that loads are increased at bus 5. The Fig. 4 also show that voltage collapse occurs at time t = 72 secs when PTSI at bus 5 approach 1.0, at time t = 73 sec when VCPI at bus 5 reach unity, at time t = 76 sec when the L index at bus 5 approach 1.0 and at time t = 73 sec

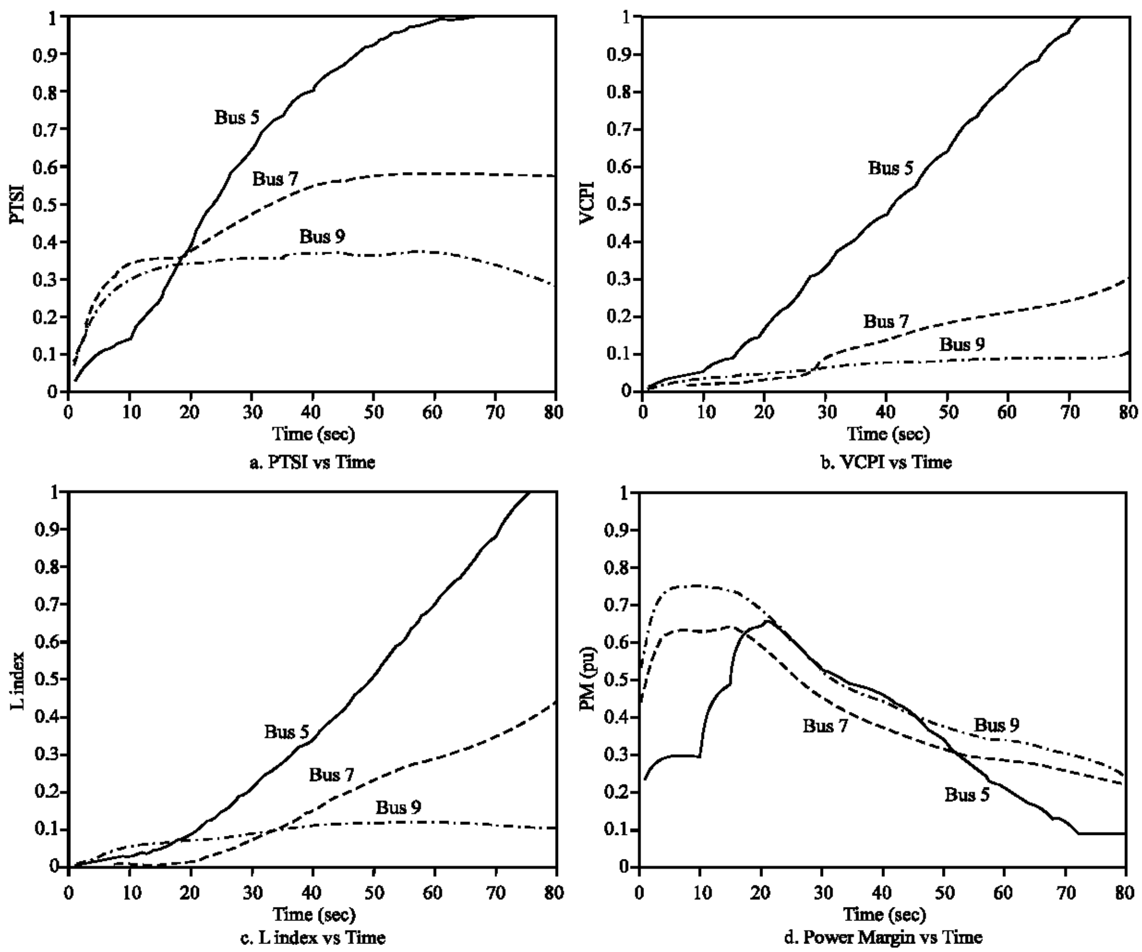


Fig. 4: Comparing the indices due to increase in load at bus 5

Table A.1 Voltage stability indices due to load increase at bus 5

Time (sec)	V4	V5	V6	V7	V8	V9
Voltage (per unit)						
1	1.0329	1.0273	1.0336	1.0287	1.0328	1.0262
10	0.9723	0.9475	0.9813	0.9557	0.9725	0.9416
20	0.9321	0.8566	0.9406	0.9187	0.9436	0.9019
30	0.8849	0.7358	0.8612	0.8642	0.909	0.8564
40	0.8491	0.6452	0.7858	0.8145	0.8797	0.8197
50	0.8202	0.569	0.7272	0.7783	0.859	0.7948
60	0.7985	0.511	0.6901	0.7556	0.8456	0.7793
70	0.7818	0.4674	0.6565	0.7356	0.834	0.7654
71	0.7792	0.4608	0.651	0.7322	0.832	0.7629
72	0.777	0.4552	0.6459	0.7292	0.8303	0.7609
73	0.7754	0.4506	0.6412	0.7265	0.8289	0.7594
74	0.774	0.4466	0.6367	0.724	0.8277	0.7579
75	0.7726	0.4431	0.6323	0.7215	0.8264	0.7564
76	0.77	0.4367	0.6263	0.7178	0.8244	0.7541
77	0.768	0.4312	0.6205	0.7145	0.8226	0.7522
80	0.7635	0.4191	0.6051	0.7058	0.8185	0.7476

Time (sec)	PTSI 5	PTSI 7	PTSI 9	VCPI 5	VCPI 7	VCPI 9	L 5	L 7	L 9	PM 5	PM 7	PM 9
Voltage stability indices												
1	0.0257	0.0774	0.066	0.0093	0.004	0.0064	0.0016	0.0002	0.003	0.3688	0.5732	0.7439
10	0.1349	0.3403	0.2932	0.0509	0.0176	0.0329	0.0261	0.0068	0.0473	0.5527	0.803	1.0534
20	0.3825	0.3705	0.3419	0.1581	0.0271	0.0462	0.0848	0.0126	0.066	1.2911	0.7762	1.0137
30	0.6377	0.4665	0.3507	0.3268	0.0823	0.0614	0.2071	0.0656	0.0865	1.3696	0.6358	0.866
40	0.8021	0.5449	0.364	0.4711	0.1344	0.0732	0.3377	0.1463	0.1071	1.1379	0.5481	0.7883
50	0.9188	0.5711	0.3641	0.638	0.1802	0.0808	0.5016	0.2286	0.1172	0.7907	0.4707	0.7091
60	0.9816	0.5783	0.3676	0.8155	0.2098	0.0851	0.6956	0.2863	0.1189	0.4016	0.4296	0.663
70	0.9992	0.577	0.341	0.959	0.2395	0.0896	0.8777	0.3417	0.1146	0.0875	0.3953	0.6295
71	0.9998	0.575	0.3293	0.9814	0.2444	0.0905	0.9058	0.3502	0.1118	0.0395	0.389	0.6237
72	1	0.5737	0.3191	0.9996	0.2493	0.0912	0.9311	0.3589	0.1094	0.0009	0.3834	0.619
73	1	0.5734	0.319	1	0.254	0.0916	0.9541	0.3674	0.1101	0	0.3789	0.6141
74	1	0.5733	0.3151	1	0.2587	0.092	0.974	0.376	0.1096	0	0.3745	0.6102
75	1	0.5732	0.3076	1	0.2632	0.0925	0.9907	0.3844	0.108	0	0.3703	0.6072
76	1	0.5714	0.3008	1	0.2691	0.0932	1	0.3946	0.1066	0	0.3641	0.6007
77	1	0.5704	0.2989	1	0.2751	0.0936	1	0.4052	0.1069	0	0.3586	0.5945
80	1	0.57	0.2909	1	0.2916	0.0947	1	0.4357	0.1065	0	0.3452	0.582

Table A.2 Voltage stability indices due to outage of line 4-5

Time (sec)	V4	V5	V6	V7	V8	V9
Voltage (per unit)						
1	0.9279	0.8168	0.9498	0.9318	0.9551	0.9106
10	0.8941	0.7484	0.8555	0.866	0.9174	0.8684
19	0.8937	0.748	0.8547	0.8654	0.917	0.8687
20	0.8938	0.7481	0.855	0.8656	0.9171	0.8688
21	0.9602	0.518	0.7594	0.8219	0.912	0.8964
22	0.9613	0.4771	0.7323	0.8073	0.9073	0.8942
70	0.9562	0.4622	0.7147	0.7958	0.8997	0.8907
80	0.9567	0.4659	0.72	0.7989	0.9013	0.8916

Time (sec)	PTSI 5	PTSI 7	PTSI 9	VCPI 5	VCPI 7	VCPI 9	L 5	L 7	L 9	PM 5	PM 7	PM 9
Voltage stability indices												
1	0.5285	0.3658	0.267	0.2518	0.0249	0.0488	0.2447	0.1214	0.0838	0.8725	0.4323	0.5751
10	0.6071	0.5719	0.3258	0.299	0.1056	0.0564	0.2048	0.1718	0.0801	1.2355	0.5691	0.8383
19	0.6069	0.5666	0.3186	0.2992	0.1062	0.0556	0.2039	0.1661	0.0764	1.2396	0.5818	0.8566
20	0.6071	0.5662	0.3182	0.2994	0.106	0.0556	0.2041	0.1659	0.0763	1.2392	0.5824	0.8573
21	0.9989	0.7123	0.2029	0.9503	0.2064	0.0175	0.6275	0.2631	0.0452	0.0548	0.491	0.9142
22	1	0.7148	0.1917	0.9987	0.2374	0.0147	0.6888	0.2696	0.0424	0.0012	0.4881	0.9097
70	0.9986	0.753	0.3306	0.9461	0.2871	0.0101	0.8431	0.2212	0.0474	0.0364	0.62	1.1142
80	0.9985	0.7468	0.3332	0.9445	0.2801	0.0109	0.8424	0.2173	0.046	0.0381	0.6285	1.1133

when the power margin at bus 5 approaches zero. The numerical values of the indices are given in Appendix A for the purpose of clarity.

Results due to outage of line connecting bus 4 to bus 5: For the second contingency case, the composite load at bus 5 has been changed to a constant load type and a line outage at the line connecting bus 4 to bus 5 is considered as a contingency. The loads at bus 5, 7 and 9 are kept constant at 1.45+j 0.98 per unit, 0.91+j 0.32 per unit and 1.12+j 0.45 per unit, respectively. Fig. 5a,b and d show that voltage collapse occurs at time t = 22 sec when the

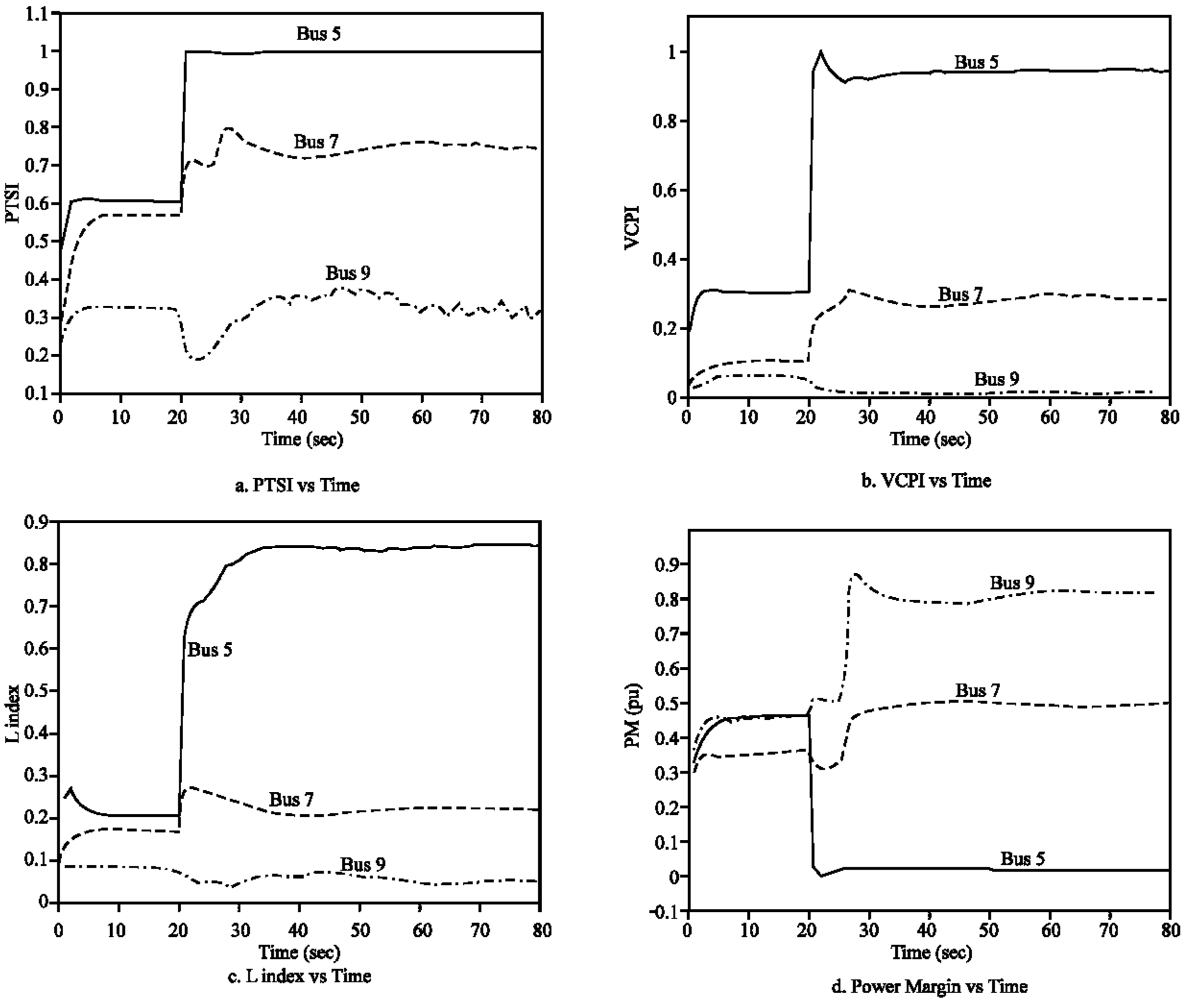
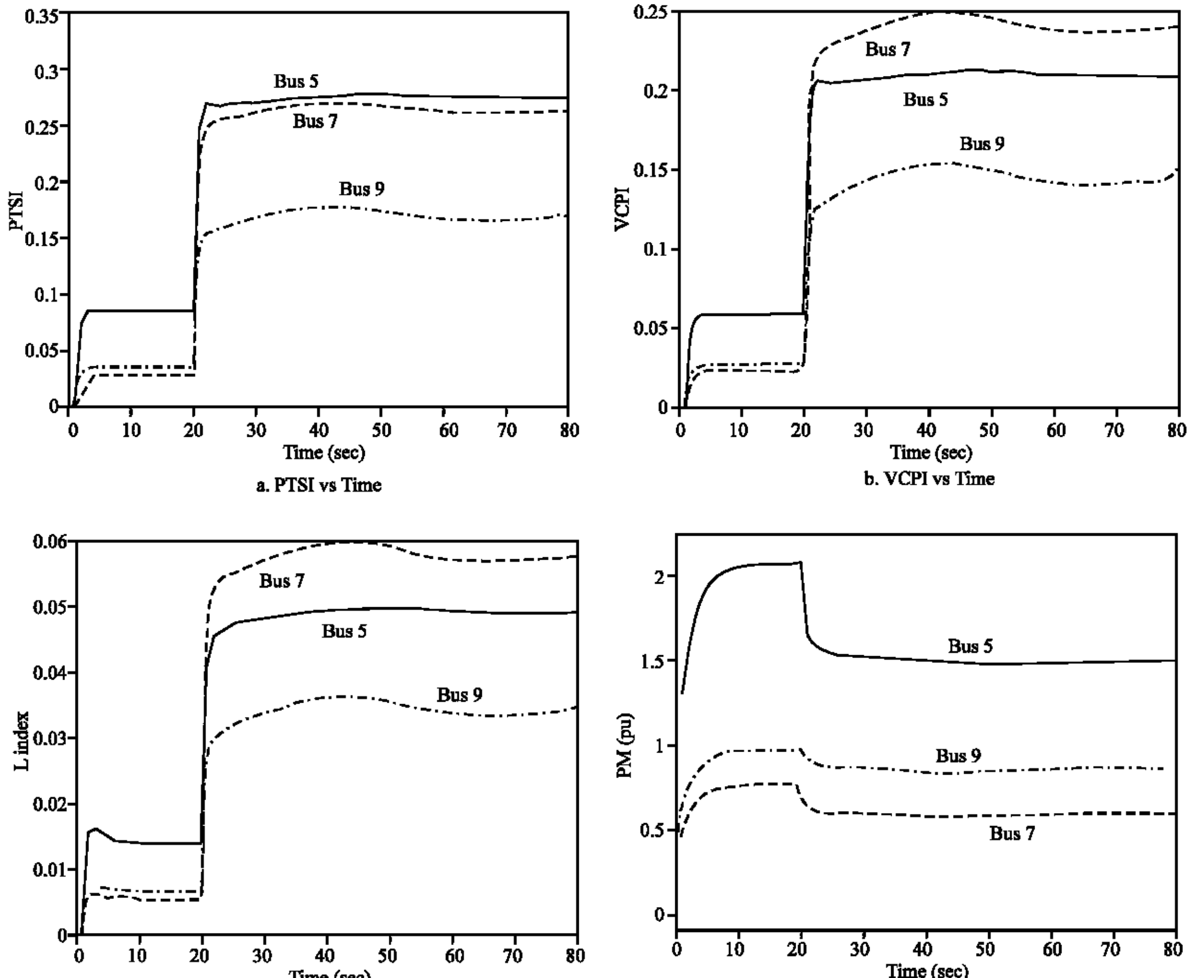


Fig. 5: Comparing the indices due to outage of line 4-5

Table A.3 Voltage stability indices due to outage of generator 3

Time (sec)	V4	V5	V6	V7	V8	V9
Voltage (per unit)						
1	0.9279	0.8168	0.9498	0.9318	0.9551	0.9106
10	0.8941	0.7484	0.8555	0.866	0.9174	0.8684
19	0.8937	0.748	0.8547	0.8654	0.917	0.8687
20	0.8938	0.7481	0.855	0.8656	0.9171	0.8688
21	0.8632	0.7046	0.7728	0.8054	0.8763	0.8363
22	0.8624	0.7017	0.7644	0.7999	0.8734	0.8346
70	0.8705	0.7092	0.7712	0.8061	0.8808	0.8379
80	0.8713	0.7104	0.7721	0.8066	0.8809	0.8375

Time (Sec)	PTSI 5	PTSI 7	PTSI 9	VCPI 5	VCPI 7	VCPI 9	L 5	L 7	L 9	PM 5	PM 7	PM 9
Voltage collapse indices												
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.3304	0.4735	0.6064
10	0.0845	0.0275	0.0341	0.0584	0.0219	0.0269	0.0138	0.0053	0.0065	2.1059	0.7718	0.9851
19	0.0845	0.0275	0.0341	0.0584	0.0219	0.0269	0.0137	0.0052	0.0064	2.1248	0.7790	0.9945
20	0.0845	0.0275	0.0341	0.0584	0.0219	0.0269	0.0137	0.0052	0.0064	2.1250	0.7792	0.9947
21	0.2505	0.2166	0.1376	0.1890	0.1886	0.1135	0.0412	0.0456	0.0274	1.7163	0.6465	0.9112
22	0.2699	0.2468	0.1526	0.2060	0.2188	0.2171	0.0455	0.0528	0.0306	1.6340	0.6264	0.9034
70	0.2731	0.2607	0.1655	0.2087	0.2365	0.1410	0.0489	0.0568	0.0334	1.5289	0.6023	0.8804
80	0.2731	0.2631	0.1686	0.2089	0.2399	0.1442	0.0489	0.0575	0.0342	1.5318	0.5974	0.8730



a. PTSI vs Time

b. VCPI vs Time

c. L index vs Time

d. Power margin vs Time

Fig. 6: Comparing the indices due to outage of generator 3

indices PTSI and VCPI at bus 5 approach unity and the power margin at bus 5 approach zero. However, the L index gives a maximum value of 0.843 which is far from unity and voltage collapse is said to occur when the L index reaches this value. From the results shown in Fig. 5, it can be considered that bus 5 is more prone to voltage collapse compared to bus 7 and bus 9 by observing that the values of PTSI, VCPI and L indices at bus 5 are higher compared to the index values at bus 7 and bus 9. This is due to the fact that bus 5 is connected to the outaged line.

Results due to outage of Generator 3: For the third contingency, outage of generator 3 is considered and occurs at time t = 20 seconds. The composite loads at bus 5, bus 7 and bus 9 are fixed at 1.45+j 0.98 pu, 0.91+j 0.32 p.u. and 1.12+j 0.45 p.u., respectively. Fig. 6a-d show the plot of voltage stability indices PTSI, VCPI, L index and power margin, respectively. From the Fig. 6a-d, the values of the voltage stability indices PTSI, VCPI and L index are relatively low, that is, very much less than 1.0 and the power margin is relatively high which is very much greater than zero. This means that the outage of generator 3 is not a severe contingency and therefore voltage collapse will not occur because generators at bus 1 and bus 2 can still supply sufficient powers to the system.

CONCLUSIONS

This research has presented the performance of the proposed index, PTSI in predicting dynamic voltage collapse by comparing it with other known voltage stability indices. From the simulation results, it can be concluded that the performance of the PTSI in dynamic voltage collapse prediction is comparable to the

VCPI and the power margin. The proposed PTSI is also sensitive in detecting dynamic voltage collapse in which voltage collapse is said to occur when the PTSI value reaches 1.0. Results also prove that the indices PTSI, VCPI and power margin give faster and better voltage collapse prediction than the L index. Future works is to verify the performance of the proposed PTSI on a practical and large sized power systems.

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